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Removing nitrogen from wastewater with side stream anammox: What are the trade-offs between environmental impacts?

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ABSTRACT

Anaerobic ammonium oxidation (anammox) is a novel way to reduce nitrogen in ammonium rich wastewater. Although aquatic eutrophication will certainly be reduced, it is unknown how other environmental impacts may change by including anammox in the treatment of wastewater. Here, life cycle assessment (LCA) was used to assess the environmental profile of a full scale wastewater treatment plant over its complete life cycle. Changes in the environmental profile by introducing a two-step anammox system in the side stream were assessed based on monitoring data from the full scale Dokhaven wastewater treatment plant (Rotterdam, The Netherlands). Our results confirmed that the two-step anammox technique further reduced life cycle nitrogen emissions compared to the regular treatment of nitrogen in wastewater. This led to a decrease in marine eutrophication potential of 16% for the total wastewater treatment plant. However, our LCA results showed that these ammonium reductions came at the cost of increasing climate change and other environmental impacts. Climate change impacts increased with 9% going from a traditional wastewater plant to the one including two-step anammox, due to increased direct emissions next to electricity use. Our LCA highlights trade-offs when adding two-step anammox for nitrogen removal in wastewater treatment systems. This has significant implications for other WWTPs as these trade-offs should not neglected when implementation of anammox is considered.

1. Introduction

Reducing nitrogen in effluent of wastewater treatment plants is one of the major goals to prevent aquatic eutrophication. The European Water Framework Directive (2000/60/EC) calls for the implementation of the Urban Waste Water Directive (92/271/EEC). According to this directive a discharge limit of 10–15 mg N/l is applicable for European wastewater treatment plants (WWTP) to sensitive areas, depending on the size of the community and that 70–80% of the initial amount of N present in the influent is removed. Half of these (2.3–4 mg N/l) concentrations might be achievable according to the Dutch water research body (Stowa, 2013). In the United States 3 mg N/l for nitrate and nitrite have been discussed (TaskGroup, 2009). According to monitoring reports (CBS et al., 2014) nitrogen concentrations in the North Sea are twice the legal limits, indicating that marine eutrophication should be considered as a relevant environmental problem in this area.

Several authors (Vidal et al., 2002; Foley et al., 2010a; Lederer and Rechberger, 2010; Rodriguez-Garcia et al., 2011) highlighted the trade-off between more nitrogen removal on one hand and higher energy demand, and related greenhouse gas emissions on the other hand when comparing different levels of wastewater treatment. Higher energy and chemical demands generally lead to higher costs.

Anaerobic ammonium oxidation (anammox) has been successfully applied as a cost effective ammonium removal process for wastewater streams with high nitrogen load (e.g. Jetten et al., 2002). During anammox, ammonium and nitrite are directly coupled under anoxic conditions to form dinitrogen gas. Anammox bacteria can perform this transformation without the need for costly aeration or an external carbon source such as methanol. Since their postulation in the 1970s and their discovery in 1990, anammox bacteria have been the focus of a growing body of research (see Kuenen (2008) for an overview). Potential energy benefits have been postulated for anammox in WWTPs that eliminate the trade-off between enhanced nitrogen removal on the one hand and other environmental problems related to energy use on the other hand (Kartal et al., 2010; Joss et al., 2009; Siegrist et al., 2008). Others (Fux and Siegrist, 2004) also estimate economic benefits of anammox over nitrification-denitrification.

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Currently, several full scale anammox reactors are implemented in WWTPs (see Gustavsson, 2010 for an overview). These reactors treat ammonium rich water, mostly reject water from digesters before it is returned to the mainstream water line. The elevated temperature and high nitrogen load of the reject water provides preferable conditions for anammox bacteria. The anammox process is either preceded by aerobic ammonium oxidation to obtain an ammonium and nitrite mixture in about equal quantities (partial nitrification, van Dongen et al., 2001), called two-step anammox, or, increasingly, anammox and aerobic ammonium oxidation are combined in one reactor (one-step anammox).

Several authors have described start-up and nitrogen removal performance of several types of full scale anammox reactors and report NH_4^+-removal efficiencies up to 90% (van der Star et al., 2007; Abma et al., 2010; Rosenwinkel and Cornelius, 2005; Frijters et al., 2007). Joss et al. (2009) also compared greenhouse gas emission from a one-step anammox reactor treating reject water to conventional nitrification-denitrification in the mainstream water line. Although they found slightly higher N_2O emissions from the one-step anammox system, total greenhouse gas emissions were lower due to lower CO_2 emissions from aeration electricity and no carbon source addition. Desloover et al. (2011) investigated treatment of industrial reject water after retrofitting with a combination of partial nitrification, anammox, and nitrification-denitrification. They found dischargeable effluents below 10 mg N/l and reduced energy requirements, but higher N_2O emissions. Not taking into account N_2O emission, Wett and Hell (2008) also found reduced ammonium emissions and energy requirements for two full scale reject water treatment plants.

However, for assessing the environmental benefits of adding anammox for reject water treatment, the overall environmental performance of a wastewater treatment plant has to be assessed. Life cycle assessment (LCA) is a well-suited method to include all environmental impacts, also those arising for provision of materials and energy (Corominas et al., 2013; Guinée et al., 2002). Beyond above assessments of nitrogen and greenhouse gas emissions and energy use during nitrogen removal and one paper by Thibodeau et al. (2014), no life cycle assessments on anammox are known to us. Information on environmental performance can help municipal wastewater treatment boards to decide on investing in this new technology or indicate focus points for further optimization.

The aim of this research was to assess the environmental life cycle implications of nitrogen treatment by a full scale wastewater plant including two-step anammox in the sidesteam. Long-term data from a two-step anammox process in the reject water treatment in Rotterdam, The Netherlands, was used for this purpose. Comparison to the same WWTP with no extra nitrogen removal from the reject water before recirculation to the mainstream water line is also included to assess environmental benefits and trade-offs.

2. Materials and methods

2.1. System description

The WWTP in Rotterdam Dokhaven was built in 1987 and currently treats about 620,400 person equivalents municipal wastewater. The local river that receives the Dokhaven WWTP effluent is a branch of the River Rhine close the North Sea. The WWTP is an activated sludge plant with biological nutrient removal. Within the mainstream water line there is an activated sludge system divided in two steps and chemical phosphorus removal (with iron chloride dosing). The first step, a highly loaded A-stage (Adsorption) with mainly BOD removal, is followed by a B-stage ("Belebung": Aeration) with low sludge load where nitrification can occur. The sludge is treated at a separate sludge line located nearby (called Sluisjesdijk). Sludge is digested before transport to an incineration plant. Reject water is recycled to the mainstream wastewater treatment plant. Biogas produced during digestion is used to generate heat for the digester and electricity for internal use. In case heat supply by the biogas is insufficient to fulfil heat needs, natural gas is added. A SHARON (Stable High rate Ammonia Removal Over Nitrite) reactor was in full operation from 1999 to 2004 in the side stream. The current two-step anammox process, with the SHARON reactor running as partial nitrification reactor, was at full load in 2005. A schematic overview of the WWTP including sludge line and two-step anammox and the system boundaries of the LCA, is given in Fig. 1.

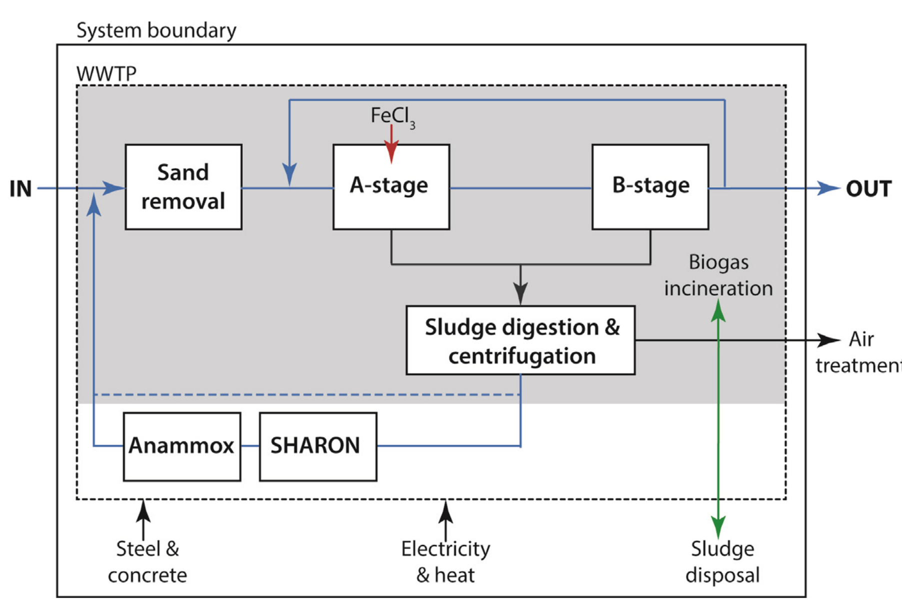

Fig. 1. Schematic representation of the WWTP in Dokhaven with the nitrogen removal configuration investigated in this research (foreground system) and the system boundaries employed. The grey box indicates the WWTP Dokhaven situation in 1998, used for the comparison of a WWTP without nitrogen removal with the two-step anammox system. The stripped blue line represents effluent recirculation before implementation of sludge line treatment. Blue lines indicate water, brown lines sludge, green lines biogas, red lines chemical input.

Table 1
Inventory data for the Dokhaven WWTP with two-step anammox in the sludge line.

Parameter	Unit	Two-step anammox	Source
Influent			
N_{tot}	kg/yr	1.66E+6	(WSHD, 2012)
Effluent[A]			
N_{tot}-N	kg N_{tot}/kg $N_{tot,in}$	0.37	(WSHD, 2012)
P_{tot}-P	kg P_{tot}/kg $N_{tot,in}$	0.02	(WSHD, 2012)
Arsenic	kg/kg $N_{tot,in}$	0.03	(WSHD, 2012)
Cadmium	kg/kg $N_{tot,in}$	2.42E−03	(WSHD, 2012)
Chromium	kg/kg $N_{tot,in}$	0.02	(WSHD, 2012)
Copper	kg/kg $N_{tot,in}$	0.09	(WSHD, 2012)
Lead	kg/kg $N_{tot,in}$	0.09	(WSHD, 2012)
Nickel	kg/kg $N_{tot,in}$	0.08	(WSHD, 2012)
Zinc	kg/kg $N_{tot,in}$	0.44	(WSHD, 2012)
Energy- and chemical consumption			
Electricity A-stage	kWh/kg $N_{tot,in}$	1.44	(WSHD, 2012)
Electricity B-stage	kWh/kg $N_{tot,in}$	2.95	(WSHD, 2012)
Electricity aeration SHARON	kWh/kg $N_{tot,in}$	0.37	(WSHD, 2012)
Electricity anammox	kWh/kg $N_{tot,in}$	0.03	(WSHD, 2012)
Net electricity water line/sludge line, other[B]	kWh/kg $N_{tot,in}$	3.85	(WSHD, 2012)
Methanol consumption SHARON	kg/kg $N_{tot,in}$	n.a.	
Natural gas consumption	MJ/kg $N_{tot,in}$	3.12	(WSHD, 2012)
Ironchloride	kg $FeCl_3$ (40%)/kg $N_{tot,in}$	0.99	(WSHD, 2012)
Material for infrastructure			
Concrete	m^3/kg $N_{tot,in}$	1.15E−03	Data WHSD
Steel anammox reactor	kg steel/kg $N_{tot,in}$	2.90E−4	T. Hendrickx, personal communication
Coating anammox reactor	m^3/kg $N_{tot,in}$	2.97E−10	(Claassen et al., 2009)
Sludge- and biogas production			
Sludge[D]	kg wet weight/kg $N_{tot,in}$	9.42	(WSHD, 2012)
Biogas[A]	m^3/kg $N_{tot,in}$	1.31	(WSHD, 2012)
Air emissions			
CO_2 fossil from methanol	kg CO_2/kg $N_{tot,in}$	n.a.	Calculated from carbon content assuming full oxidation
Direct fossil CO_2	kg CO_2/kg $N_{tot,in}$	6.00E−01	(Foley et al., 2010b, Law et al., 2013)
CO_2 fossil from biogas combustion	kg CO_2/kg $N_{tot,in}$	1.72E−01	See SI
N_2O-N emissions SHARON	kg N_2O-N/kg $N_{tot,in}$	4.03E−03	(Kampschreur et al., 2008)
N_2O-N emissions Annamox	kg N_2O-N/kg $N_{tot,in}$	6.88E−04	(Kampschreur et al., 2008)
N_2O-N emissions A-stage	kg N_2O-N/kg $N_{tot,in}$	3.09E−03	(Kampschreur et al., 2008)
N_2O-N emissions B-stage	kg N_2O-N/kg $N_{tot,in}$	3.95E−02	(Kampschreur et al., 2008)
NO-N emissions SHARON	kg NO-N/kg $N_{tot,in}$	4.74E−04	(Kampschreur et al., 2008)
NO-N emissions Annamox	kg NO-N/kg $N_{tot,in}$	4.74E−06	(Kampschreur et al., 2008)
NO-N emissions A-stage	kg NO-N/kg $N_{tot,in}$	4.76E−05	(Kampschreur et al., 2008)
NO-N emissions B-stage	kg NO-N/kg $N_{tot,in}$	4.74E−04	(Kampschreur et al., 2008)
Direct CH_4[C]	kg CH_4/kg $N_{tot,in}$	7.95E−02	(Kampschreur et al., 2008)

(A) Part of the sludge that is treated in Sluisjesdijk is from other treatment plants. Nitrogen from this external sludge is considered outside the system boundaries and subtracted from the effluent data. Likewise, biogas and electricity generation were reduced to exclude credits from other WWTP. (B) The WWTP in Rotterdam is build underground, which requires additional ventilation efforts. Electricity generation was subtracted from this electricity use to derive net electricity use for ventilation. (C) For WWTP without sludge digestion GWRC (2011) reports a emission factor of 20% lower. Therefore 20% of direct CH_4 emissions were attributed to sludge treatment and 80% to the mainstream water line. (D) For disposal of sludge, the ecoinvent process 2.2 'Disposal, digester sludge, to municipal incineration' was employed (see Supporting information).

2.2. Comparison

Wastewater treatment in Rotterdam Dokhaven was compared using LCA based on the ReCiPe method (Goedkoop et al., 2012). ReCiPe was chosen because it is a state-of-the-art life cycle impact assessment methodology that covers a wide range of environmental impacts. Treatment of one kg of total nitrogen of inflow (hereafter: kg N_{in}) was chosen as functional unit. To enable easy comparison with other LCA studies on wastewater treatment, a functional unit of 1 $m^3{}_{in}$ treated was also employed. The wastewater composition and nitrogen load for the WWTP in the year 2011 has been taken as a reference (Table S1). The nitrogen inflow into the WWTP in 2011 was 36 g/m^3 in 2011 (WSHD, 2012). Effluent numbers and biogas production were reduced to exclude input from sludge originating from other WWTP that was also treated at Dokhaven. Lifetime assumed for the anammox reactor material were 15 years based on calculations by Stowa (Stowa, 2010). For the total WWTP the lifetime before the installation of the anammox reactor was added to these 15 years, resulting in a total lifetime of 34 years.

2.3. Inventory data

Data for the WWTP with two-step anammox were reported by the waterboard Waterschap Hollandse Delta (WSHD, 2012) and refer to the year 2011. N_2O and NO emissions to air were taken from Kampschreur et al. (2008), who measured these emissions for Dokhaven in one year. Kampschreur et al. (2008) report N_2O-N emissions as percentages of the N-inflow per reactor (1.7% for the SHARON reactor, 0.36% for the anammox reactor). These data were converted to emission factors of kg N_2O and kg NO per kg N_{in} for the A and B-stage, the SHARON/partial nitrification reactor and the anammox reactor. The inventory data per kg N_{in} are shown in Table 1, the inventory based on 1 $m^3{}_{in}$ is shown in the Supporting information (Table S2).

Emissions of CH_4 from the WWTP were included as percentage of COD in the influent based on national inventory guidelines (IPCC, 2006; GWRC, 2011). CO_2 emissions from the WWTP were calculated assuming all total organic carbon (TOC) becomes oxidized to CO_2. Total organic carbon was taken as 26% of COD inflow (Foley et al., 2010b). 7% of the direct CO_2 emissions from the WWTP were

Table 2
N total in effluent per kg N total in the traditional, SHARON and two-step anammox scenario.

Traditional	SHARON	Two-step anammox
kg N_{tot}/kg $N_{tot,in}$	kg N_{tot}/kg $N_{tot,in}$	kg N_{tot}/kg $N_{tot,in}$
0.44	0.41	0.37

assumed to be of fossil origin, for example from detergents, following Law et al. (2013). The biogenic fraction of CO_2 emissions were not taken into account in the life cycle impact assessment because these likely derive from food crops with short growth cycles and therefore are considered to have a negligible influence on global warming (Cherubini et al., 2011). Additionally, CO_2 emissions from combustion of biogas were estimated based on the carbon content (fom Wilsenach and van Loosdrecht, 2006) and amount of biogas generated. Only the fraction (7%) that was assumed to be of fossil origin was taken into account as direct CO_2 emissions. CO_2 emissions from provision and consumption of natural gas were taken from ecoinvent (see Supporting Information for more detail).

WSHD (2012) reported an electricity use for aeration of the partial nitrification reactor of 2.6 kWh per kg NH_4-N in the reactor influent for 2011. For comparison, electricity use for areation in the A and B stages summed up to 4.4 kWh per kg N total in (see Table 1).

2.4. Comparison with traditional WWTP

To assess the environmental benefits or drawbacks of implementing anammox in the sludge line of the WWTP, the impacts of the WWTP with two-step anammox were compared to impacts from traditional wastewater treatment with only nitrification–denitrification in the main line, reject water recirculation and no additional nitrogen removal from the digester reject water. Additionally, an intermediate scenario, where nitrogen is removed from the reject water in sludge line via SHARON was included. These assessments were based on data from the same WWTP before implementation of the anammox (unpublished waterboard data). Table 2 shows the differences in N effluent between the three scenarios, the complete inventory for these scenarios is shown in Tables S4a and S4b.

2.5. Sensitivity and uncertainty analysis

To assess the robustness of the results and the effects of uncertainty in inventory data on the impact results, uncertainty estimates were included. In the uncertainty analysis, the following parameters were assessed:

– Higher total nitrogen emissions: Total nitrogen emissions fluctuated over the years during which the two-step anammox was used in Dokhaven. Emissions were low in 2011 (the year calculations were based on). Therefore, results are also presented for the year with highest total nitrogen emissions (2010 based on data from WSHD).
– Ranges for N_2O emissions from two-step anammox and water line: N_2O emissions were based on measurements in one year and might be subject to changes. For full scale anammox and partial nitrification reactors, few measurements of greenhouse gas and in particular N_2O emissions are available in the literature for different reactors for the separated steps (Joss et al., 2009; Desloover et al., 2011; Kampschreur et al., 2008; Mampaey et al., 2011; Kampschreur et al., 2009a; Okabe et al., 2011; Law et al., 2011). Therefore, alternative low and high N_2O emission factors from the anammox and partial nitrification reactor were taken from literature referring to lab studies (Okabe et al., 2011, Law et al., 2011) (see Table S5) to estimate possible ranges in N_2O emission from the two-step anammox system. For N_2O emissions from the mainstream water line high and low values were also taken from literature (Kampschreur et al., 2009b).
– Nitrogen emissions from other anammox process configurations could be different. Joss et al. (2009) report N_2O emissions and electricity use and Kampschreur et al. (2009a) report N_2O emissions from one-step anammox reactors treating reject water. We used their reported data to replace the emissions and electricity from our two-step anammox. No data are available that cover a complete WWTP with one-step anammox, therefore we assumed the rest of the WWTP to be equal to our study. These calculations are indented to give a first impression on how performances compare (see Table S6).
– Lower electricity use for partial nitrification reactor: Electricity use for the partial nitrification reactor was high in 2011 compared to earlier years and also assessed with an alternative value from another year (2010 based on data from WSHD).
– CH_4 emissions from WWTP: Emission factors per COD influent were applied to estimate CH_4 emissions (IPCC, 2006, GWRC, 2011, Doka, 2007). Daelman et al. (2012) report ranges in CH_4 emission factors from 0.008 to 0.013 kg CH_4/kg COD in the influent for WWTPs with an anaerobic digester. These are used to assess possible uncertainty in results due to uncertainty in CH_4 emission factors.
– Infrastructure needs depend on the lifetime of the WWTP. Lifetimes are estimates based on literature and current age. Actual usage years of WWTP infrastructure might deviate from these numbers. Therefore as sensitivity test a factor of 10 higher or lower infrastructural needs for the anammox reactor and the WWTP were also included.

3. Results

Fig. 2 shows the contribution of different parts of the WWTP (direct emissions, two-step anammox, electricity and 'iron chloride dosage for phosphorus removal') to each impact category. Direct emissions from the WWTP encompass effluent emissions of nitrogen compounds, phosphorus and metals and greenhouse gas emissions to air. Two-step anammox related emissions encompass electricity and infrastructure for the two-step anammox reactors and direct N_2O emissions from these reactors. 'Other' encompasses impacts from provision of natural gas, and sludge disposal. Absolute characterized impact scores are shown in Table S7 in the Supporting Information for kg N_{in} and $m^3{}_{in.}$ Direct water emissions of nitrogen compounds and metals contributed dominantly to marine eutrophication and to human and aquatic toxicities, respectively. Direct greenhouse gas emission from the WWTP contributed dominantly to climate change. Provision of iron chloride contributed dominantly to ozone depletion. Iron chloride also contributed most to terrestrial acidification, water depletion, metal depletion, land occupation and transformation. The contribution of the two-step anammox was small for all impact categories, but highest for climate change.

3.1. Comparison to WWTP without additional nitrogen removal

Fig. 3 compares the marine eutrophication and climate impacts of the WWTP Dokhaven with two-step anammox with traditional wastewater treatment without anammox (based on Dokhaven in 1998). The differences in impacts between the SHARON and the traditional WWTP are also shown. Climate change impacts were 9% higher for two-step anammox and marine eutrophication impacts were 16% lower for two-step anammox compared to the traditional WWTP. For the comparison of the SHARON scenario with the traditional WWTP, a decrease in marine eutrophication (5%)

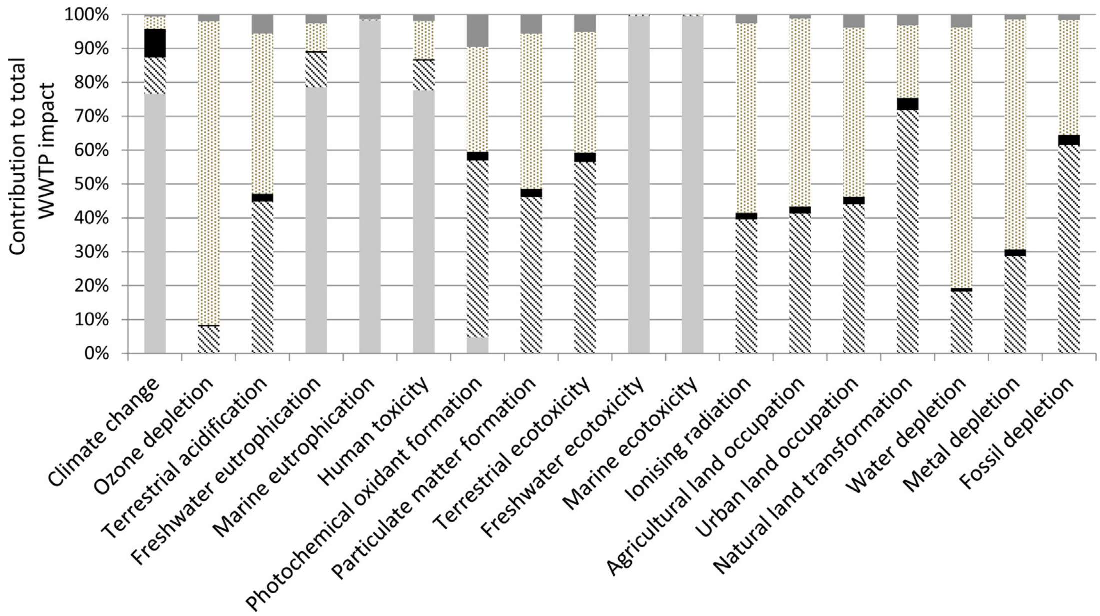

Fig. 2. Contribution of parts of the WWTP Dokhaven to the total impact of treating 1 kg N_{in} for each impact category: diagonal stripes: electricity; light grey: direct emissions from WWTP; black: all interventions related to the two-step anammox; dotted: iron chloride; dark grey: other processes.

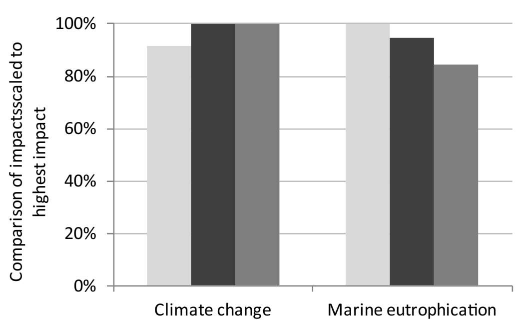

Fig. 3. The impacts scores for marine eutrophication potential and climate change for the two-step anammox, the SHARON and the traditional WWTP scaled to the highest impact (light grey indicates the traditional scenario, black the two-step anammox, dark grey the SHARON scenario).

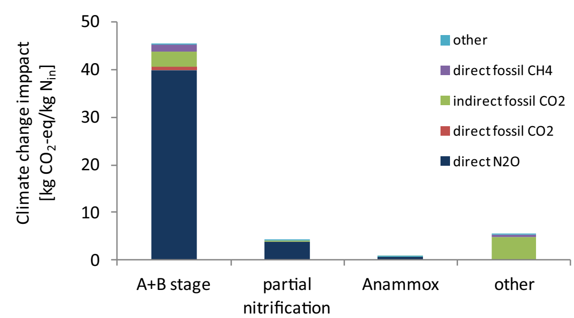

Fig. 4. Contribution of different process stages in the two-step anammox WWTP. The category 'Other processes' refers to electricity use for general ventilation, natural gas consumption and sludge disposal. The contribution of the various greenhouse gases per process step is also shown.

was found and an increase in climate change comparable to the two-step anammox WWTP. All other impacts increased by less than 3% for the two-step anammox scenario (see Fig. S2). Most impacts increased 2–3% due to increase in electricity use. Impact categories more influenced by direct emissions, such as toxicity and freshwater eutrophication impacts increased less than one percent. Impacts increased slightly more for the SHARON scenario (with maximum of 10% for natural land transformation, see Fig. S1) related to methanol consumption in addition to increased electricity use. As can be seen in Fig. 2 marine eutrophication impacts are for almost 100% caused by direct nitrogen emissions from WWTP. Contributions to climate change are shown in more detail in Fig. 4.

The contribution of direct and upstream emissions to climate change impacts from the WWTP with two-step anammox can be seen in Fig. 4. Climate change impacts were mainly caused by direct greenhouse gas emission from WWTP, including biogas combustion. The main contributors were N_2O emissions from the water line (mainly B-stage).

3.2. Sensitivity and uncertainty results

Higher total nitrogen emission increased marine eutrophication impacts by 33%. Table 3 shows changes in climate change impacts

Table 3
Changes in climate change impacts due to changes in parameters assessed in the sensitivity and uncertainty analysis in percentage relative to the original result.

Traditional	SHARON	Two-step anammox
kg Ntot/kg Ntot,in	kg Ntot/kg Ntot,in	kg Ntot/kg Ntot,in
0.44	0.41	0.37

derived with values for the uncertainty ranges compared to the original results. Uncertainty in N_2O emissions from the water line had the highest impact on results. However, these uncertainties exist for a WWTP with and without anammox. Uncertainties that occur only for the WWTP including two-step anammox (above dotted line in Table 3) were much smaller and mainly related to N_2O emissions from the partial nitrification reactor.

4. Discussion

The discussion starts with a critical assessment of the uncertainties in the LCA of WWTP with two-step anammox, including the results from the sensitivity analysis. After that, the results are interpreted regarding the differences between WWTP with and without anammox and the contribution of different processes to climate change from the two-step anammox. Finally, other potential nitrogen removal technologies are shortly discussed.

4.1. Uncertainties

Some aspects could not be taken into account in the current study, such as minor infrastructural changes, such as pumps for the SHARON and anammox reactors and the provision of biomass to start the anammox reactor. Infrastructure for the whole WWTP was approximated by the use of concrete. As the total WWTP is built on piles in a former harbour and underground, use of concrete was expected to be a dominant aspect of infrastructure material. Other infrastructural changes are not expected to influence results significantly, as the influence of major infrastructure for the anammox reactor and the WWTP on our results was small (e.g. changes <1% in the sensitivity analysis). Fig. 4 also showed a negligible influence of the reactor material of the anammox reactor on total climate change impacts (within indirect CO_2 emissions from anammox reactor). Other authors (Ortiz et al., 2007; Remy and Jekel, 2008), however, found that infrastructure, including the sewage system, and assembly could contribute up to 20–40% to total impact for overall impact or some impact categories (energy demand, abiotic depletion, climate change and human toxicity), highlighting, these conclusions could be very case- and system boundary specific.

4.1.1. Uncertainty estimations

Our calculations were performed for the year 2011. However, total nitrogen emissions fluctuated between 2007 and 2011. Total nitrogen removal efficiencies in these years varied from 51% to 63% (average 58%). For SHARON in the side stream, efficiencies ranged from 52% to 60% over the years 2002–2004. This ranges in nitrogen removal efficiencies are reflected in the uncertainty in marine eutrophication potential.

N_2O emissions from anammox and partial nitrification reactors might be subject to uncertainties. Grouping together the lowest emissions for the anammox and partial nitrification reactors on the one hand and the highest emissions of both reactors on the other, leads to greenhouse gas emissions that could be 3% lower or 10% higher respectively, for the combined two-step anammox. In our study, N_2O emissions from the mainstream water line (particularly the B-stage) contributed most to global warming impacts. In our study emissions were about 4% for the mainstream water line. However, ranges reported in literature are high. In a review of activated sludge processes in the United States, Ahn et al. (2010) found a range of 0.01–4.8% of N_2O emission of Kjeldahl nitrogen inflow. Kampschreur et al. (2009b) indicated ranges in N_2O emission from full scale wastewater treatment of 0–14.6% of the influent nitrogen. Taking this largest range led to the largest variation in climate change impact in Table 2, highlighting the need for improved understanding of N_2O emissions from wastewater treatment.

According to several sources (Mampaey et al., 2011; Kampschreur et al., 2009b; Ahn et al., 2010) N_2O emissions are largely influenced by oxygen and nitrite levels, indicating that process management likely can influence N_2O emissions levels at least to a comparable extent as technology choice. In our study, measurements from the WWTP under consideration were applied. These are expected to be the best estimates for our case study. However, transferring absolute numbers to other WWTP will likely be accompanied by high uncertainties.

4.2. Interpretation of the results

4.2.1. Comparison of WWTP with and without anammox

Results are related to the total WWTP to show the effects of full scale implementation of anammox. The plant had a total nitrogen removal efficiency of about 60%. However, efficiency of the anammox reactor for N (total) was about 85–90% (WSHD, 2012). This difference is explained by the relatively small contribution of the reject water to the total influent (less than 20%).

Next to climate change, other environmental impacts (with exception of marine eutrophication) also increased from the traditional WWTP to the one with two-step anammox due to electricity and material use in the non-traditional scenario. Increases were even higher for the SHARON reactor, particularly for ozone depletion and natural land transformation. These additional increases were due to methanol consumption (4% of the increase for ozone depletion and 2% for natural land transformation). Although electricity use for reactors is used for aeration as in other WWTPs, total absolute electricity use numbers should not be extrapolated because the WWTP in Rotterdam is build underground and therefore requires additional ventilation efforts. The influence of electricity use on most environmental impacts categories of wastewater treatment has also been shown by other authors (Pasqualino et al., 2009; Hospido et al., 2008; Ortiz et al., 2007) and is confirmed by our results.

Direct GHG and in particular N_2O emissions, however, were only taken into account in one of these studies (Pasqualino et al., 2009). Several authors (Desloover et al., 2011; Rodriguez-Garcia et al., 2012) highlighted the importance of taking into account N_2O emissions as they might be more influential than climate change impacts from electricity use by WWTPs. Rodriguez-Garcia et al. (2012) report that direct N_2O emissions can be a factor of 8 higher than CO_2 equivalent emissions related to electricity use. We found a factor of 5 higher contributions of direct N_2O emissions compared to CO_2 emissions from electricity production in the anammox scenario. Higher N_2O emissions, mainly from the partial nitrification reactor, led to higher climate change impacts for the two-step anammox scenario. This is consistent with findings by Desloover et al. (2011). They investigated a system including a two-step anammox approach and identified that the partial nitrification reactor was an important source of N_2O emissions. Schaubroeck et al. (2015) compared a one-stage partial nitrification-anammox system for side stream treatment to nitrification-denitrification for side stream treatment and an one-stage partial nitrification-anammox system in the main line (replacing the B-stage). They also conclude that N_2O emissions should be controlled for the one step anammox to achieve an overall environmental benefit.

Schaubroeck et al. (2015) report N_2O emissions from the one step anammox of 1–1.3% of the N in the inflow, which is slightly higher than our values. For one stage anammox in the mainline, they even report N_2O emissions of about 2% of nitrogen input. For nitrification–denitrification in the sideline Schaubroeck et al. (2015) report N_2O emissions of 1.3–6.5%, which encompasses our mainline values. For nitrification–denitrification in the mainline, however, they report about 0.007%, a value substantially lower than ours (about 4% for A and B stage). Emissions from the two step anammox system in our study, on the other hand, were about 0.5%, indicating, in our case anammox could lead to lower N_2O emissions if replacing nitrification-denitrification.

The climate change trade-off of reduced N emissions using anammox depends on the magnitude of N_2O emissions in the original system. If mainline N_2O emissions are lower than in our case, the increase in N_2O emissions from an anammox system would be relatively more important. With the mainline nitrification-denitrification emissions found by Schaubroeck et al. (2015), even the emissions from the two-step anammox found in our study would be a substantial addition to the emissions without sludge-line treatment. For lower N_2O emissions, the relative contribution of electricity input to climate change could increase. This could also be the case for a lower internal electricity production (which was about 24% in our case in 2011 for biogas from Dokhaven sludge). Possibly, accumulation of N_2O can be decreased by reducing the anoxic period (Kampschreur et al., 2008). Avoiding the anoxic period altogether would likely demand another reactor design and requires further research (Kampschreur et al., 2008).

Other considerations, such as investment and maintenance costs, can be important for technology choices. Stowa (2008) reports investment and operational costs for using a SHARON reactor and a two-step anammox. Transferring these to our functional unit, for Dokhaven 2011, results in a cost-effectiveness advantage for the anammox reactor of about 30% (0.15 vs. 0.20 €/kg N_{in}). These calculations are detailed in the Supporting Information.

4.3. Conclusions

We found that anammox can achieve higher nitrogen removal than no side stream treatment or use of SHARON only without increase in electricity use due to the anammox reactor, in line with earlier calculations (Kartal et al., 2010). However, the electricity use increased for the partial nitrification reactor. Furthermore, increased N_2O emissions from the partial nitrification reactor could offset benefits from using anammox. Thibodeau et al. (2014) found that using nitrification-anammox in the sidestream increased climate change impacts compared to a system without sidestream treatment, due to the N_2O emissions. In our study, N_2O emissions from the partial nitrification reactor were relatively small compared to the main line. This indicates, N_2O emissions also from traditional nitrification-denitrification should not be neglected in LCA studies of wastewater treatment.

Our results are widely important for wastewater treatment as trade-offs should be considered when choosing anammox. For wide spread implementation of anammox, alternative configurations, such as smaller reactors allowing for less aeration, or a one-step anammox with low aeration should be considered. Joss et al. (2009) and Kampschreur et al. (2009a) found lower N_2O emissions from a one-step anammox reactor than for the partial nitrification reactor in Dokhaven (see Table 2). Next to reactor design, N_2O emission might be influenced by process management such as aeration cycles. Joss et al. (2009) found lower N_2O emission when continuous aeration was used. Contrastingly, Domingo-Felez et al. (2014) found lower N_2O emissions, with shorter and more frequent aeration stages.

If low temperature anammox would replace nitrification–denitrification in the mainstream water line of the WWTP, as currently investigated (e.g. Hu et al., 2013; Lotti et al., 2014) but not yet implemented in a wastewater treatment plant, larger eutrophication benefits may be found, without increasing or even reducing climate change effects. For example, transferring the nitrogen removal efficiency of the anammox reactor to the main line could improve the overall nitrogen removal efficiencies from about 50% to about 85% (for 2010 data) and reduce electricity use as well. However, first results by Schaubroeck et al. (2015) indicate one stage anammox in the mainline could provide larger environmental benefits than side stream treatment, but highlight that increased N_2O emissions could also occur in this configuration. The WWTPs investigated in their studies, were designed for energy self-sufficiency, indicating anammox in the mainline could decrease chemical and electricity usage, even for comparable nitrogen removal efficiencies. Further research on this one-step anammox configuration as well as reducing N_2O emissions is recommended.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2015.11.019.

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